8. Conclusions and Suggestions for Future Work

Conclusions and Suggestions for Future Work

This thesis has described the development of an articulated skeletal analogy of the human upper-limb. The stimulus for this work has come from the needs of amputees who currently must chose between prostheses that either appear outwardly like the original limb and posses limited or no function and devices mechanistic in appearance that provide some useful functionality. The prostheses provided to amputees have not significantly changed since the clinical introduction of the myoelectric prosthesis in the 1970’s (Kostuik 1980). Research efforts have largely focussed on refining these historical prosthetic designs (Banerjee 1982, Parker and Scott 1988). Additionally, incremental developments from these archetypes appears to have resulted in further division of function and cosmesis.

Amputees require both functionality and cosmesis from their prostheses (Fraser 1998). It is only the limitations of currently available prosthetic technology that necessitate amputees to proiritise between cosmesis and function (Tura 1998, Herder 1998, Fraser 1998).

The starting point for the work in this thesis was the proposition that design principles appropriate to a future generation of prostheses combining both cosmesis and functionality in a single device would only result from the close analogy to the human upper-limb. A crucial first step in this process is the development of a close analogy of the articulations of the skeletal limb, which not only could form the basis of a prosthesis, but might also be used to test appropriate actuation and control strategies. Therefore, the aim of this research was to elucidate design principles to construct such an analogy.

The method used to develop designs for the articulated model limb have been based on close observation of the original anatomy (Conrad *et al* 1995) and the production of physical models / prototypes (Archer 1995). Models have been used to refine initial joint ideas to more resolved prototypes suitable for quantitative and qualitative evaluation. Tangible objects have been used to enable a broad evaluation of the design principles and thereby add to subsequent stages in the design process (Archer 1995).

The resulting models have been evaluated to assess the closeness of the anatomical analogy achieved. The subtleties of human movement and joint structure indicate that quantitative evaluations may not be sufficient. Additionally, the human skeletal limb is not self supporting, but rather is dependent on soft tissue connections for some of its form and function (Kapandji 1982). Therefore, measurements at the surface may not reflect movements at the skeletal level. For these reasons a process of qualitative evaluations by professionals with extensive anatomical knowledge was undertaken. The models have additionally been reviewed by a wide range of ‘end-users’. These are primarily amputees but occupational therapists, prosthetists, prosthetics manufacturers and leading prosthetics researchers have also been consulted to assess any practical outcomes that might result from the model limb. In addition, criticism has been sought from researchers involved in the development of novel muscle like actuators in the hope that production of a tangible model would stimulate interest in the application of these technologies to the development of a future prosthetic device.

Both the qualitative and quantitative evaluations performed on the models indicate that the model joints have achieved a close level of analogy with the articulations of the human limb. Additionally, review of the model by end-users, indicates both short and long term applications for the design principles embodied in the model.

Evaluations

Throughout the research difficulties have been experienced comparing the ranges of movement of the model joint with those reported for intact human joints. This has principally been caused by the absence of an analogy for soft tissue within the model.

Problems caused by soft tissue coverage of the intact joints appeared particularly acute in the evaluation of the forearm. To validate the designs measurements were required on intact joints which are deep within soft tissue and which display a complex coupling (Kapandji 1982, Amis 1990). However, the difficulties experienced in this work in measuring intact human joint movement have been experienced by other researchers investigating the movement of the forearm (Youm et al 1978).

Therefore, it appears appropriate to use the qualitative evaluations to compliment the quantitative methods.

Qualitative evaluations for comparing the model joints with the articulations of the human limb involved visual and tactile examinations of the model. The materials used in the model have quite different colours and textures to those of the human arm and there is no soft tissue covering the model. Significantly, the lack of soft tissue was commented on as a factor impeding evaluation. Suggestions for possible tests with the model covered with a suitable cosmetic cover were made by one participant in the evaluation to enable him to more closely assess the model joints against those of the human limb. However, the visual differences between the model and the human limb appeared advantageous in assessing the potential of the model to form part of an eventual prosthesis. For example, features such as the modularity of the finger joints were easily recognised due to the contrast of between the metallic struts and the black plastic joints.

Qualitative evaluation also indicated that a ‘damping quality’ was absent from the joints. It was also suggested that this could be achieved within the model by incorporating analogies for the soft tissues. Again, this could not be incorporated into this first model as its detailed design arose from close observation of the skeletal human limb, with no soft tissue attached to it.

The skeletal structure was taken as the basis for the mechanical analogy described in this thesis, as it is the fundamental anatomical structure from which the form and function of the limb arise (Kapandji 1982). However, the limitations of informing design principles mainly from observation of skeletal anatomical models have become evident. Therefore, future design cycles may be further informed on the significance of soft tissue through MRI scanning on live subjects and observational drawing studies of the ligamentous and tendinous structures revealed in cadavers.

Modifications to Research Method

The research method adopted, which is a form of practice led design research (Archer 1995) required both supplementation and revision as the research progressed.

In the original implementation of the research method, the first stage, the analytical stage, combined observational drawing with sketchbook idea development and literature review. During the development of the distal and proximal radio-ulna joints it was found that the observational drawing and sketchbook idea development in the analytical stage was insufficient. It was found too difficult to visualise the potential effects of different mechanical configurations which mimicked the complex coupled movements of the linked distal and proximal joints. Therefore, during the development of the forearm joints it was necessary to add mathematical analysis to the analytical stage to aid the investigation of potential mechanical configurations.

Implementing the iterative nature of the research method, where evaluations feed into subsequent cycles of design work, has not been as straightforward as initially envisaged. It has become evident that the cyclical development of the articulations of the limb was not always appropriate. This was especially evident in the development of the forearm and elbow joints where the functions of the proximal radio-ulnar joint were not separable from the functions of flexion and extension of the elbow.

Additionally, as the research progressed it became evident that small iterative cycles incorporating an evaluation were not always appropriate. Meaningful evaluation of the model appeared only to be possible when significant anatomical sections were complete. For example a whole hand form was necessary for the quantitative assessment of the ranges of movement of the joints of the fingers using goniometric techniques.

Both the limitations of method in developing the forearm and elbow joints, and the difficulties experienced in gaining a meaningful evaluation from isolated components of the model necessitated revising the research method, in particular revising it to permit the development of joint designs concurrently. Where joints were developed separately, such as the second iteration wrist joint, this was because the design appeared to be a significantly less successful analogy than the other joints.

Joint Principles Derived Sensitive to Context

It was found that many principles elucidated using observational drawing from specific joints were not portable to other joints of the limb. This was especially evident in the evaluation of the first model wrist. The mechanical analogies developed from observation of the joints of the fingers did not appear to be readily transferable to the wrist. Instead, it was found that close observational studies were required for each joint.

Limitations of Mechanical Analogy

Initially, the model hand was developed with a view to actuating the wire tendons extrinsically. Therefore, analogous wire tendons were routed through the wrist to facilitate remote actuation. The tendons were 'actuated' through pulley wheels to pretension the wires and provide complimentary movements of flexor and extensor tendons. Using this method it was possible to control flexion and extension movements of the fingers. However, linking flexor and extensor tendons highlighted problems caused by mechanically coupling the movements of the fingers and the wrist. It was found that on flexion of the wrist the fingers would extend, and vice versa. Several mechanical schemes were devised on paper to compensate for wrist movement. However, a simple mechanical arrangement could not be identified. This questioned whether the use of mechanical analogy was appropriate to identify the design principles for the dynamic components of a future prosthesis. From the anatomy and physiology literature it was found that the coupling mechanism is achieved through low level spinal synapsing (neural connections) (Fox 1993). Additionally, robotics research is investigating control algorithms that mimic theories of the biological spinal chord (Hannaford et al 1995). In light of this research it was concluded that a mechanical analogy was not appropriate to mimic these mechanisms.

The identification of research into neural control strategies (Hannaford et al 1995) for the natural arm and hand, combined with evidence of 'artificial muscle' research (De Rossi et al 1992, DellaSanta et al 1997) suggested that the appropriate focus for the work should be the further development of a complete anatomically analogous skeletal model upper-limb. Which could form a platform for the outcomes of work from these other areas. In particular, such a platform could focus such work towards the requirements of a prosthesis which offers both the form and function of the natural arm and hand.

Comparisons with Previous Robotic Devices

The comparison of the kinematics and structure of the model hand to previously developed robotic hands indicates the potential for the model to form the basis for an 'artificial hand' which would aid telemanipulation using data glove control. Data glove control assumes the remote manipulator mimics the real hand, but the current generation of robotic hands have diverted from an anthropomorphic structure; either through scale (Herzinger 1995) or kinematic layout (Jacobsen et al 1984, Mason and Salisbury 1985). It has been found by researchers investigating the control of such dexterous manipulators that effective control of the 'slave' manipulator is aided if it possesses a similar arrangement of joints to those of the 'master' glove (Caldwell et al 1995 and Perlin et al 1989). Therefore, the model hand, with its kinematic arrangement derived from the articulations of the human hand may have a potential use in this field.

Additionally, the derivation of the kinematics and scale of the model hand from that of the human hand mean that the hand can potentially manipulate and grasp objects designed around the anthropometric constraints of the human hand. This has been demonstrated by configuring the model hand around many domestic products and controls (levers and handles). However, to achieve full functionality of the hand including grasp and manipulation will require extensive further research into appropriate actuation and control strategies (Jacobsen et al 1984 and DeRossi et al 1992).

More Complex Prototyping Techniques Aiding Qualitative Evaluation

As the research has progressed the joint forms developed have become more complex, and the prototype manufacturing techniques have become similarly more complex. This has resulted in the techniques used in the development of the wrist which allow not only the realisation of a complex form but also a complex embedded mechanism. Evidence in the transcribed evaluations pertaining to natural joint movement indicates that complex forms adds to the effectiveness of the analogy of the model, therefore, justifying the more complex prototyping methods used.

End-Users Involved in the Design Process

With the introduction of the model hand to the focus group, the groups expections for a future prosthesis changed. Prior to the introduction of the model hand the view voiced by the group was that they regarded prostheses as primarily cosmetic or functional. However, after the introduction of the model hand the indications from the group were that a future prosthesis combining both cosmesis and functionality could be envisaged. In the introduction given to the focus group science fiction images had been shown and this did not change the groups expectations. It appeared only with the introduction of the tangible model hand that these expectations were changed. This indicates a potential benefit for the use of models in user research.

The input of the amputees was valued and a progress report has been regularly given to this group on the state of the research and criticism invited. The literature warns against raising expectations of amputees to an unacceptable level (Curran and Hambrey 1991). Therefore, using the model as means of presentation was considered appropriate as the potentials and limitations of the model could be easily assessed by amputees.

Expectations for a Future Prosthesis

The principle finding from attendance at a regular amputee support group has been the desire from the group to see the model limb actuated. Additionally, a desire has been voiced by the group to work with other researchers from complimentary disciplines such as actuation and control to support more rapid development. Both these aspirations for the research from the support group are being addressed.

Creating Enthusiasm for a New Generation of Prostheses

Previously, the majority of prosthetic research has focussed on developing iterations on established archetypes (Banerjee 1989). However, the development of the skeletal model, embodying features that may support a practical prosthetic implementation appears to have reawakened interest in this research field. In particular, interest has been shown from researchers working on novel actuators. Currently, a model arm has been delivered to a laboratory in Pisa. These researchers are initiating experiments that apply novel actuation methods to actuate pronation / supination movements of the model forearm (Chiarelli 2000).

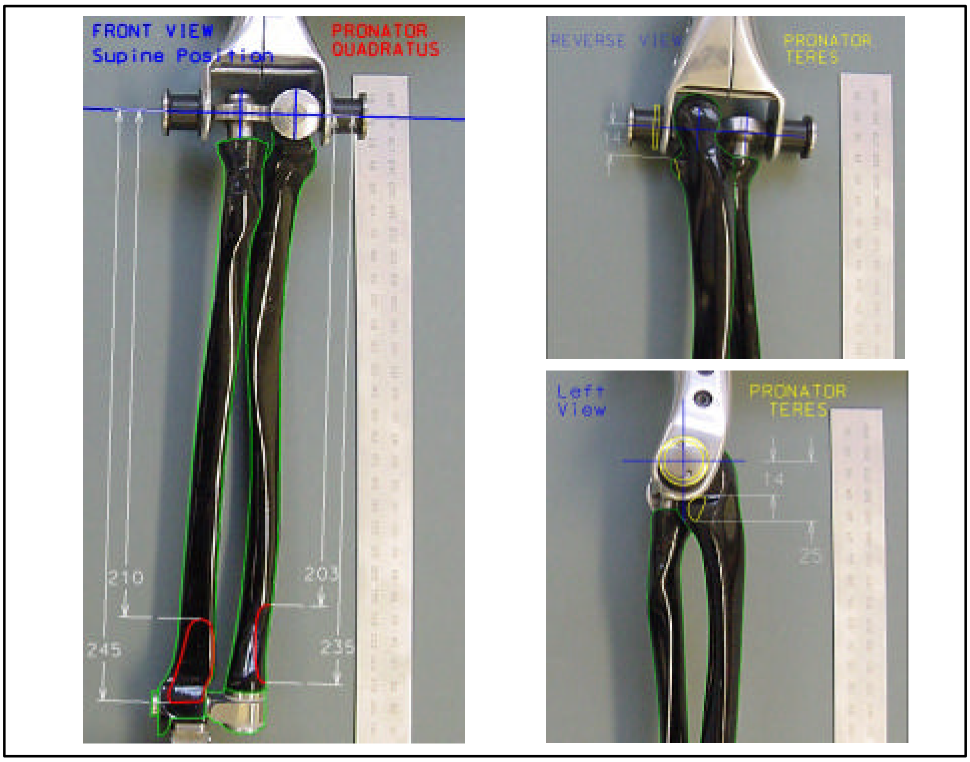

Fig 8.1 Muscle Origins and Insertions 'Mapped' onto the Model Limb

Figure 8.1 shows some initial communication with this group indicating how the muscular attachments of the human limb relate to positions on the model limb. Additionally, a replica model arm has been requested to provide a 'demonstrator' for this new actuation technology being developed in Pasadena (Bar-Cohen 2000).

Potential Short Term Implementation of Design Principles

The review of the model by both a key figure in prosthetics research and a prosthetics manufacturer have highlighted the significance of the modularity of the joints of the hand to aid the short term implementation of design ideas into prostheses. Delivery of replicas of the finger joints have been promised to one key prosthetics researcher to support his work on combining both static and dynamic cosmesis in prosthetic terminal devices (Gow 2000).

Summary

Evaluations indicate that the model limb represents a close analogy of the articulations of the human upper-limb and it embodies design principles that appear to have both short term and long term significance to the field of prosthetics.

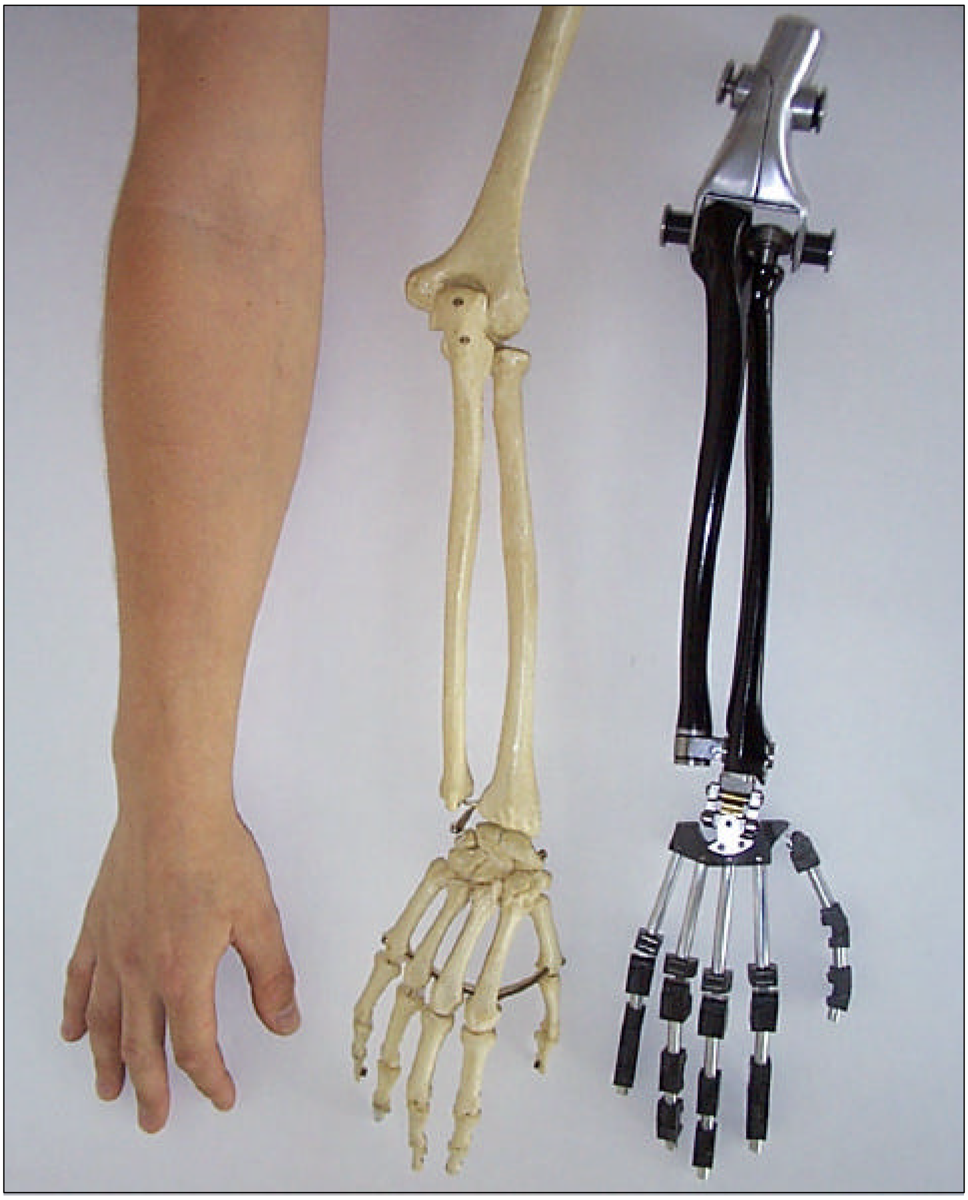

Fig 8.2 The Current Model Limb

The production of tangible models has aided the evaluation of the model and is also supporting further research into other aspects of the limb in other laboratories.

Dissemination of the model to robotics laboratories may indicate wider uses of a close skeletal analogy of the human upper-limb.

Suggestions for future work

Suspension

The need for new ideas for prosthetic suspension methods was highlighted in the focus group. Developing new design principles for this aspect of prosthetics appeared inappropriate at the time of the focus group. However, as the research has tackled more proximal joints of the limb, potential new strategies for suspension using the principles of close analogy have become apparent. These now need to be pursued.

Implantable Joint Designs

Qualitative evaluation of the model elbow and wrist joint by orthopaedic surgeons revealed that the closely anatomically analogous joints might be developed towards a ‘linked’ implantable prosthesis. Of principle interest was the potential the elbow joint showed for a method of linking the radius to the humerus whilst still permitting natural pronation / supination and flexion / extension movement. The current surgical procedure involves the excision of the head of the radius when implanting a hinge-like elbow prosthesis (Sulzermedica 1991). If this direction is pursued it appears appropriate that quantitative methods may be more prominent to ensure the structural properties of the proposed designs are appropriate. Additionally, investigations will also be needed to determine appropriate ‘biocompatable’ materials for an implantable device.

Structures for Actuation and Tendon Guidance

The evaluations of the model hand indicated that tendon guidance and joint constraints required further work. Additionally, evaluations of the quality of movement of the forearm and wrist suggested an analogy of soft tissue within model would be advantageous. One of the main aims of future work would be to develop the skeletal analogy, adding tendon guidance and actuation structures.

Structural Analogy

Whilst the original goals were to ascertain whether joints could be made that would provide close analogies of the articulations of the upper-limb evaluations of the model have indicated that form is also important in achieving a close analogy.

For example, the ‘bones’ of the model hand are simple cylinders, whilst the forms that connect the joints of the model forearm are modeled to the form of the radius and ulna bones of the human skeleton. It appears that with the use of strong lightweight materials, such as carbon fibre, these forms can be made to withstand the predicted forces on a prosthesis (Snaith 2000).

Further work is necessary to determine the level of ‘form analogy’ that will both, provide the structural requirements of a future prosthetic device, but will also support small scale modularity and effective manufacture that has been indicated as desirable.